

Massive Stellar X-ray Sources in the Galactic Center

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Abstract. We present results of a spectroscopic survey of bright near-infrared counterparts to X-ray point sources from a deep *Chandra* survey of the Galactic nuclear bulge. *K*-band spectroscopy has revealed 13 new Wolf-Rayet and O-supergiant counterparts to *Chandra* sources in the Galactic center (GC). Although they are systematically softer in X-rays than the general GC source population of accretion powered cataclysmic variables (CVs), their X-ray colors indicate a hard component consistent with emission from plasmas with $E > 2$ keV. Such hard X-ray emission is not ubiquitous among single Wolf-Rayet and O stars, but is common among Wolf-Rayet+OB binaries with colliding supersonic winds. Although we regard colliding-wind binary hypothesis as the most likely scenario, it remains possible that several of these objects are wind-accreting neutron stars or black holes in supergiant high-mass X-ray binaries, or extraordinary single stars emitting hard X-rays.

1. Introduction

The nuclear bulge of the Galaxy contains the greatest concentration of X-ray point sources in the sky (Muno et al. 2009). Although the population is dominated by cataclysmic variables (CVs), there are likely to be ~ 100 sources that are the products of massive-star evolution, including high-mass X-ray binaries (HMXBs) and colliding-wind binaries (Mauerhan et al. 2009). IR spectroscopy of bright counterparts to this population are revealing a growing number of massive stellar X-ray sources, outside of the well known Arches, Quintuplet and Sgr A^{*} star clusters (Muno et al. 2006; Mikles et al. 2006; Mauerhan et al. 2007; Hyodo et al. 2008). The identification of such objects has important implications for the mode and recent history of massive star formation in the GC, the dynamical evolution of GC stellar clusters, and the evolution of massive binaries.

Here we present the most recent discoveries of WR/O counterparts to *Chandra* X-ray sources in the GC.

2. Sample

A catalog of 9017 X-ray point sources has been assembled from *Chandra* observations of the inner $2^\circ \times 0.8^\circ$ of the Galaxy, incorporating all ACIS-I observations of the region as of 2007 September (Muno et al. 2009). Assuming a distance of 8 kpc to the GC, the catalog is complete down to $L_X > 10^{32} \text{ erg s}^{-1}$ over one square degree and an order of magnitude more sensitive in the few arcminutes around Sgr A*, where there is 1 Msec of exposure. We cross-correlated the *Chandra* GC point-source catalog with near-IR catalogs produced by the Simultaneous 3-color Infrared Imager for Unbiased Surveys (SIRIUS) on the 1.4-meter Infrared Science Facility (Nishiyama et al. 2006), and the Two-Micron All-Sky Survey (2MASS; Cutri et al. 2003). In order to select *Chandra* sources at or beyond the GC, we restricted our sample to sources having soft X-ray colors indicative of an interstellar absorbing column of hydrogen with $N_H > 4 \times 10^{22} \text{ cm}^{-2}$. The IR sample was further restricted to sources having colors with $H - K_s > 0.9 \text{ mag}$, consistent with our adopted cut-off value of N_H . Further restricting our IR sample to sources with $K_s < 12 \text{ mag}$, we produced a list of 261 X-ray/IR matches of which 61 ± 30 (2σ) should be genuine, as determined from simulations which yielded the expected number of random matches between the X-ray and infrared catalogs (see Mauerhan et al. 2009).

3. Observations

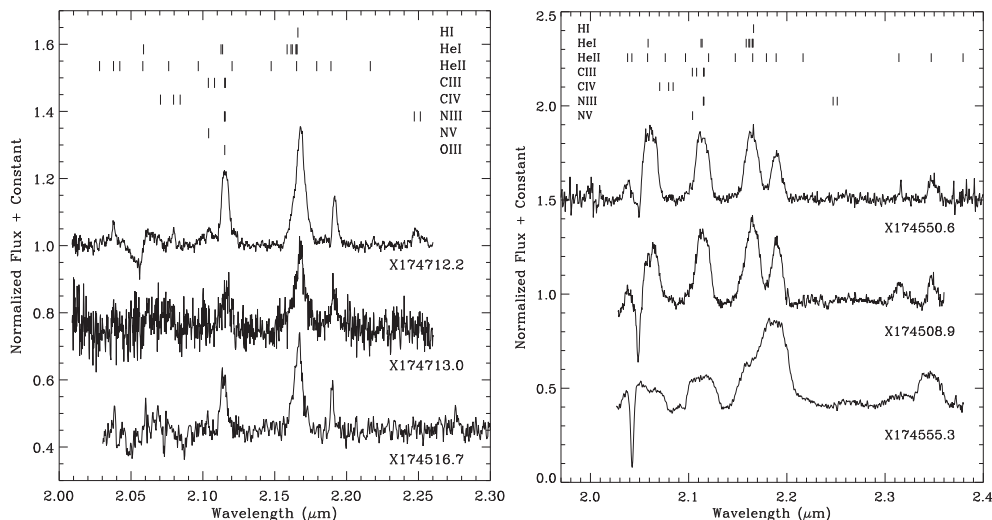


Figure 1. Example *K*-band spectra of hydrogen-rich (WN7–8h; *left panel*) and hydrogen-poor (WN5–7; *right panel*) WR X-ray sources. Broad emission lines of He I and He II dominate the spectra.

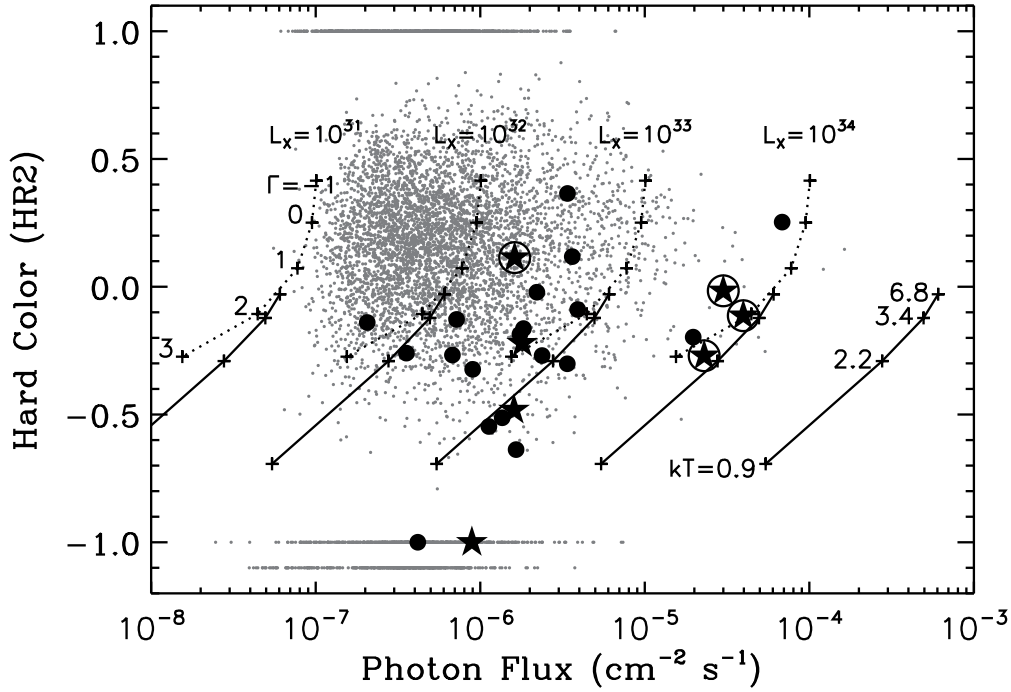


Figure 2. Photon flux vs. hard X-ray color (HR2) comparing massive-star counterparts (*large symbols*) to the field population of CVs (*small points*). Sources associated with the Arches (*filled stars with circles*) and Quintuplet (*filled stars*) clusters are also included for comparison (those from Law & Yusef-Zadeh 2004). Model tracks of thermal and non-thermal plasma absorbed by a hydrogen column of $N_{\text{H}} = 6.0 \times 10^{22} \text{ cm}^{-2}$ are plotted for comparison. The figure indicates that the majority of massive X-ray emitting stars have X-ray luminosities of $L_{\text{X}} \approx 10^{32} - 10^{34} \text{ erg s}^{-1}$ (0.2–8.0 keV).

NIR Spectra: To determine the nature of these counterparts we have been performing *K*-band spectroscopy of candidates at several observational facilities, including the IRTF, AAT, UKIRT, and Keck. So far we have identified 17 WR/O counterparts to the *Chandra* hard X-ray sources. The spectral-types span a wide range of massive-star evolutionary stages, including early to late O supergiants, Ofpe/WN9, WNh, WNE and WC stars (Mauerhan et al., in prep.). Figure 1 exhibits example *K*-band spectra of 6 of the 13 counterparts discovered. These particular spectra were obtained with UKIRT/UIST and the AAT/IRIS2, and are of moderate resolution ($R \approx 2000$). The example spectra include hydrogen-rich WN7–8h stars and hydrogen-deficient WN5–7 stars, all of which exhibit broad emission lines of H I, He II and N III. The WN5–7 stars have particularly broad flat-topped emission lines, indicative of very extended supersonic winds with $v \approx 2000 - 3000 \text{ km s}^{-1}$. The spectra of the additional discoveries, including O supergiants and WC stars, will be presented in a forthcoming paper (Mauerhan et al., in prep.).

X-ray Photometry: Figure 2 shows a plot of hard X-ray color (HR2) vs. 2–8 keV photon flux for all massive stellar X-ray sources known in the GC,

including sources from the Arches and Quintuplet clusters. HR2 is defined as $(h - s)/(h + s)$, where h and s are the fluxes in the 3.3–4.7 and 4.7–8.0 *Chandra* bands, respectively. The massive stars are systematically brighter and slightly softer in X-rays than the field population dominated by CVs, and in most cases have plasma energies above 2 keV. The data are consistent with both thermal and non-thermal emission mechanisms, and indicate that the majority of massive X-ray-emitting stars have X-ray luminosities of $L_X \approx 10^{32}$ – 10^{34} erg s $^{-1}$ (0.2–8.0 keV). Sources in the Arches cluster have relatively high X-ray luminosities.

4. The Nature of Massive Stellar X-ray Sources in the Galactic Center

Hard X-ray Emission: The hard X-ray emission ($kT > 2$ keV) observed for most of the stars in our sample is not ubiquitous among single WR/O stars. However, X-rays from WR+OB binaries with colliding, supersonic stellar winds typically exhibit a hard component. We regard this scenario as the most likely explanation, given the high binary fraction of massive stars (Mason et al. 1998), and the inevitable collision of supersonic winds involving systems containing WR stars and O supergiants. Since the X-ray luminosity of a wind collision zone is proportional to $1/D$ (Usov 1992), where D is the binary separation, Fig. 2 might be an indication that the sources of the Arches cluster are colliding-wind binaries with relatively small separations; this would not be surprising since dense stellar cluster environments, where gravitational encounters are frequent, will eventually lead to a hardening of massive close binaries.

However, we cannot yet rule out the possibility that our sample also contains wind-accreting neutron stars and black holes in HMXBs, in which case the X-ray emission may be non-thermal. If there are HMXBs in this sample, their relatively low X-ray luminosities ($L_X \approx 10^{31}$ – 10^{33} erg s $^{-1}$) compared with most known HMXBs (Liu et al. 2006) would imply a low accretion rate. If confirmed, such HMXBs would help determine the luminosity function of HMXBs at the low end, which would have implications for models of magnetic resistance to low-rate accretion of a stellar wind (Liu & Li 2006). Single-star scenarios should also be considered. O stars with strong magnetic fields can channel supersonic winds from opposite stellar hemispheres into a self-collision zone near the stellar equator. Such a model has been developed to explain the hard X-ray emission from the late-O giant θ^1 Orionis C (e.g., see Wade et al. 2006) and was also considered in the case of the oxygen-rich WR star WR142 (Oskinova et al. 2009), although the X-ray luminosity in the latter case is over an order of magnitude fainter than the faintest star in our sample.

Further observations are required to discriminate between the various scenarios discussed above. Particularly, radial-velocity measurements over several epochs could reveal the presence of companions through their Doppler motions, while allowing for a constraint on component masses. We will be performing such experiments in the near future.

Origins: Figure 3 illustrates the spatial distribution of the massive stellar X-ray sources in the GC. Given their distribution, the origin and formation mode of these stars is unclear, as all but several do not appear to be associated with

known stellar clusters in the GC region. It is possible that these objects are members of stellar clusters that had lower initial masses and densities than the Arches and Quintuplet, and so have been tidally disintegrated to the point where they are not detectable as a stellar density enhancement above the crowded background field (e.g., see Portegies Zwart et al. 2002). It is also possible that dynamical interaction within clusters may be responsible for the ejection of massive binaries, in which case a few members from our sample may have actually originated in the Arches and Quintuplet, even though they are now separated from the clusters by ~ 10 pc. Alternatively, these stars may be evidence for a mode of isolated massive star formation occurring in the GC region, in tandem with the formation of dense stellar clusters such as the Arches and Quintuplet. This may be the case for the six sources concentrated near the Sgr B H II region. The continued discovery of massive stellar X-ray sources in the GC will give a more complete picture of their overall spatial distribution, while follow-up observations aimed at surveying the stellar content of their immediate surroundings and constraining their kinematics will help elucidate the origins of these massive hard-X-ray-emitting stars.

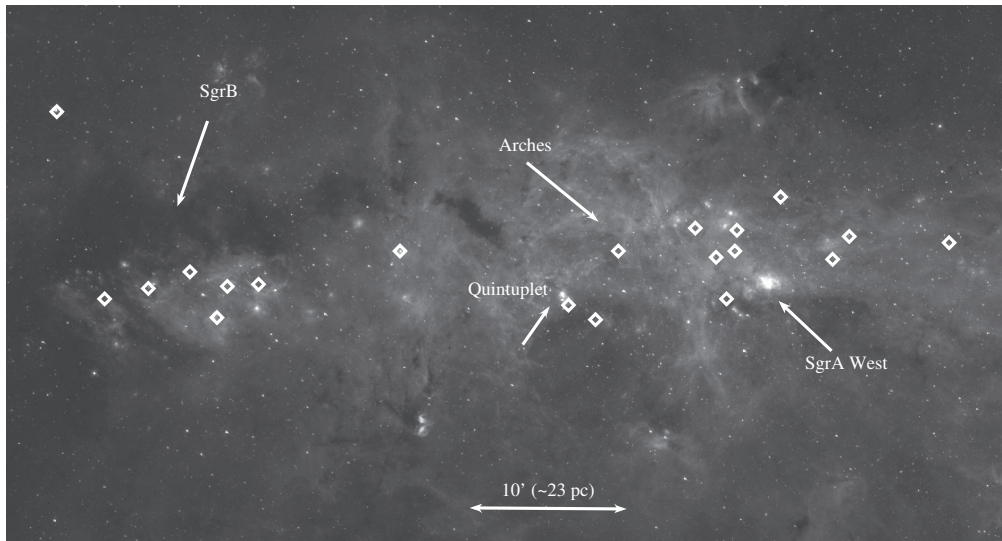


Figure 3. *Spitzer* $8\ \mu\text{m}$ image of the Galactic center region, illustrating the spatial distribution of massive stellar X-ray sources not within the Arches or Quintuplet clusters. The positions are approximate.

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